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Simulation of Bunch Formation Mu2e Longitudinal Phase Space

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Mu2e Extinction Technical Review

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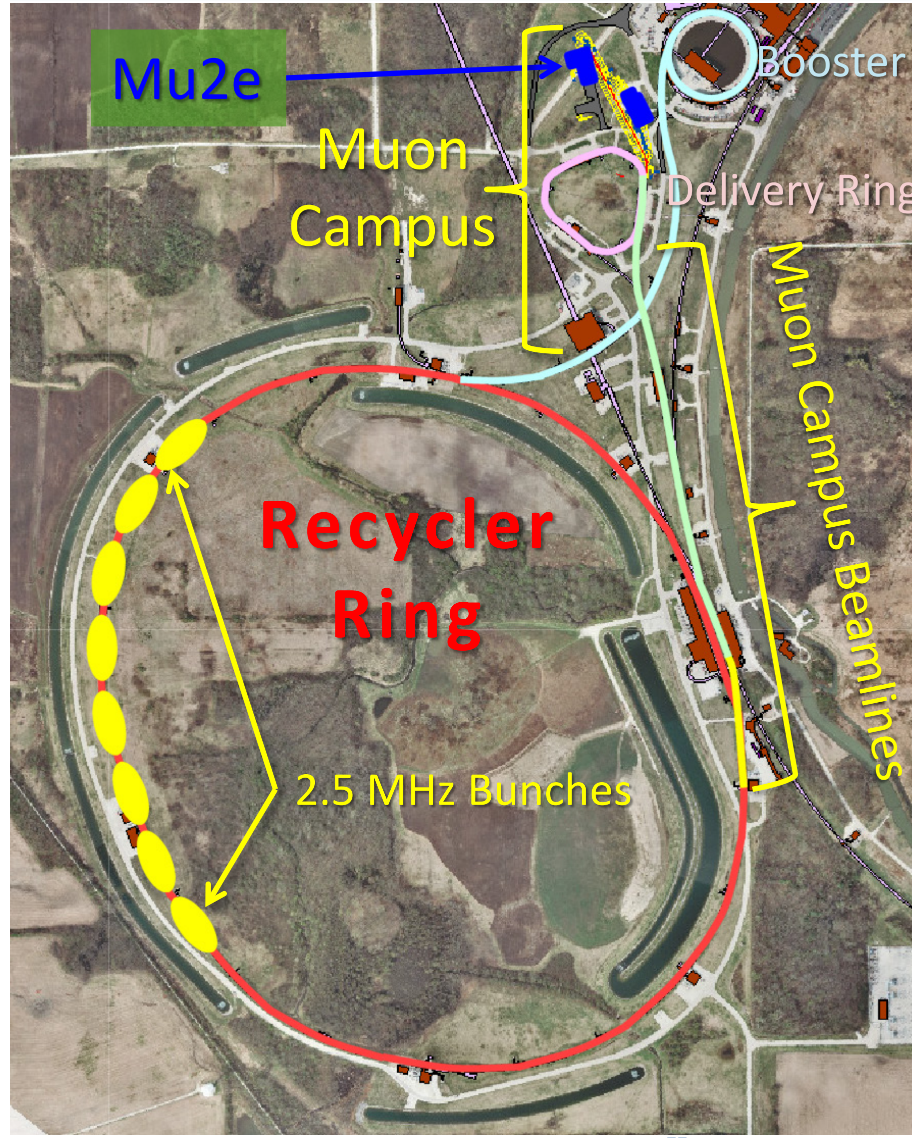
Outline

1. Mu2e Longitudinal Phase Space Manipulation
2. Longitudinal Tracking Models
   - Recycler Ring Model
   - Delivery Ring Model

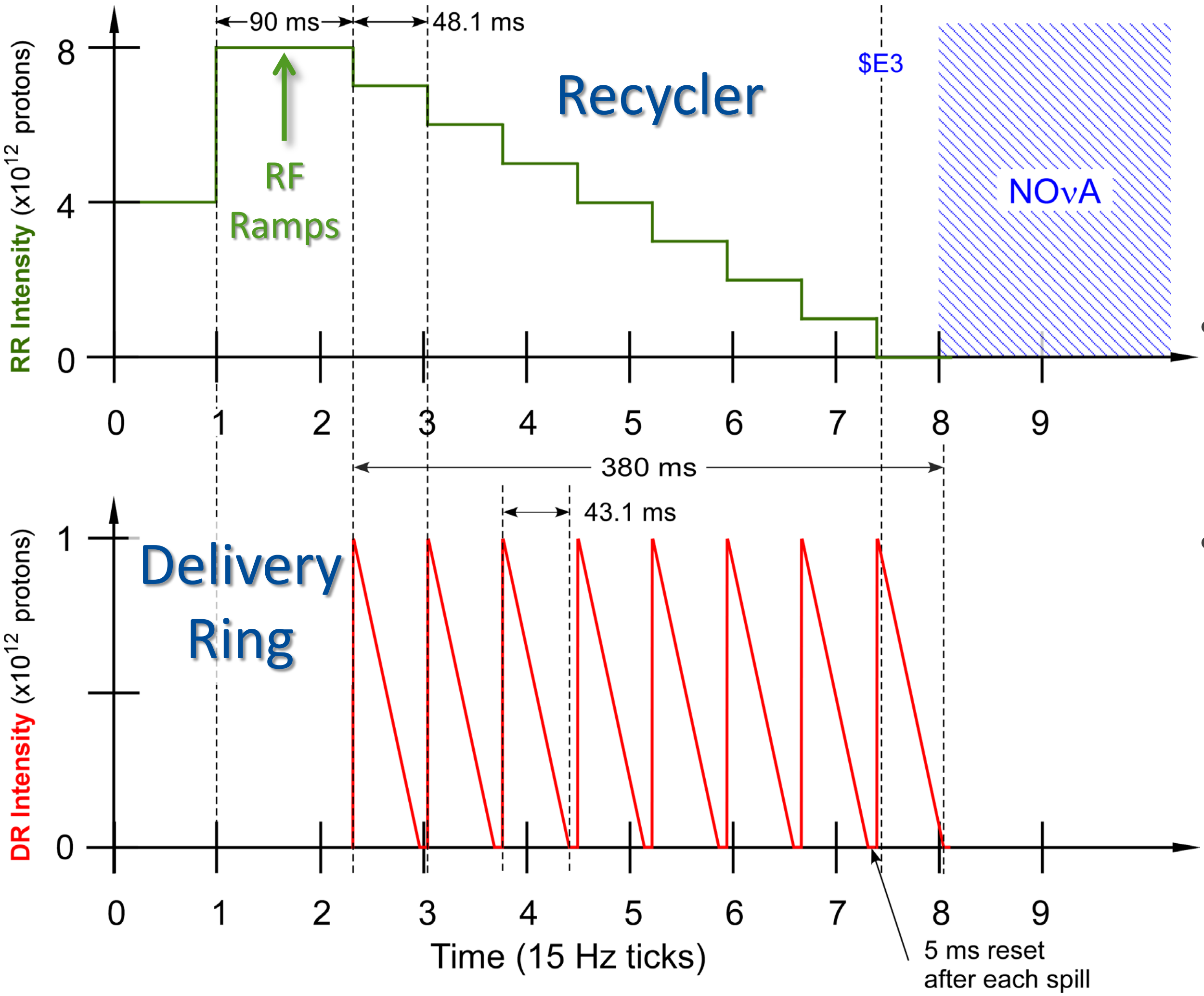
Mu2e Longitudinal Phase Space Manipulation

Acquisition of Beam for Mu2e

1. Two proton batches are transferred from the Booster to the Recycler Ring
   - One Booster proton batch = 4×10^{12} protons in 81 bunches (53 MHz)
   - Proton batch injection rate = 15 Hz
   - Two batches occupy 2/7 of Recycler circumference
2. Beam is re-bunched with a 2.5 MHz RF system
   - RF voltage ramps:
     - 5 msec ramp down of 53 MHz
     - 85 msec ramp up of 2.5 MHz
   - Result: 8 bunches
3. The 2.5 MHz bunches are extracted one-by-one into the Muon Campus beamlines and transferred into the Delivery Ring
4. Beam is synchronously captured into a 2.4 MHz RF bucket in the Delivery Ring
5. Delivery Ring beam is resonantly extracted to the M4 beamline

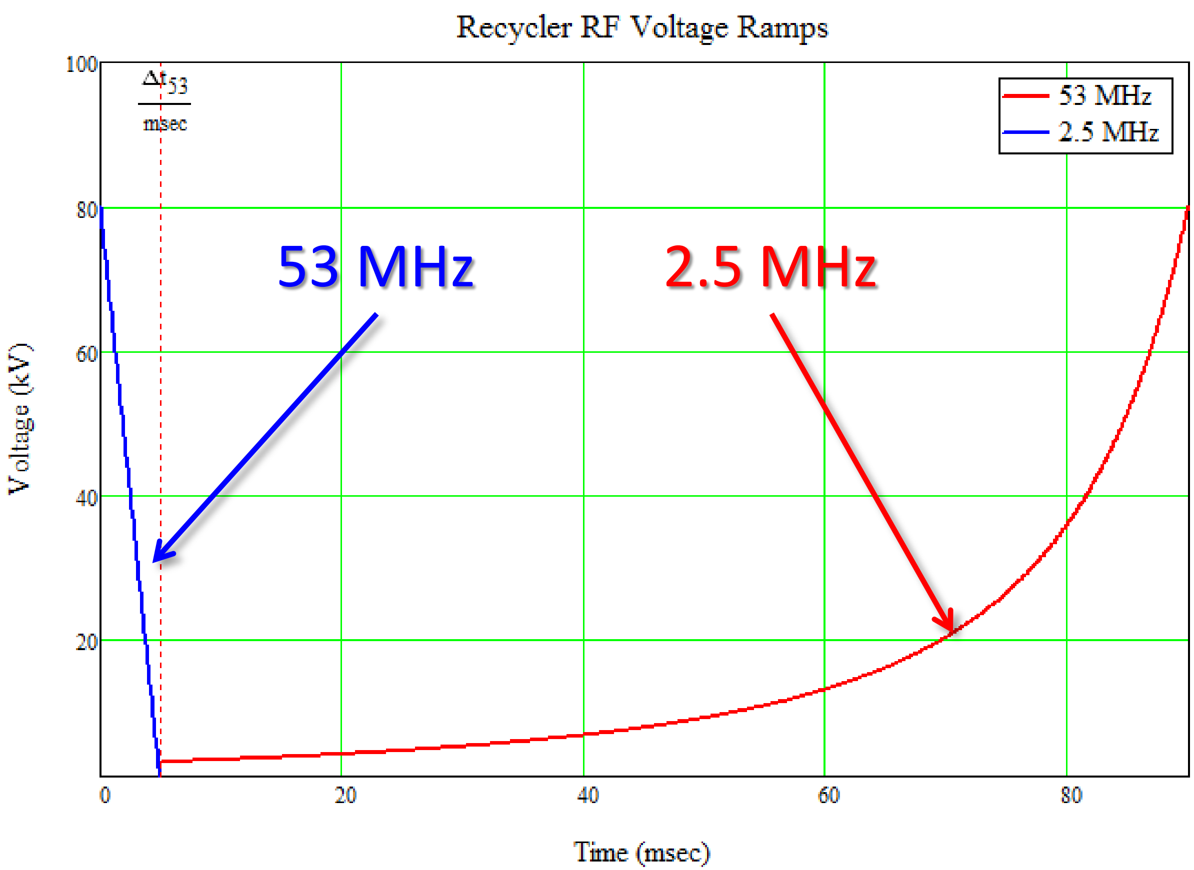


Macro Time Structure of the Proton Beam



- A bunch containing 1×10^{12} protons is transferred from the Recycler to the Delivery Ring every 48.1 msec
- Delivery Ring beam is spilled over 43 ms (~25,400 turns)
- After 8^{th} spill, beam is off for ~1 sec while NOvA uses the Recycler for slip-stacking

Recycler RF Voltage Ramps



- Synchronous transfer from Booster to Recycler into 53 MHz RF buckets at t = 0
- 53 MHz RF voltage linearly ramped to zero in 5 msec
- When 53 MHz is off, the 2.5 MHz voltage is adiabatically ramped to 80 kV in 85 msec

➢ The purpose of the 2.5 MHz re-bunching is to produce narrow (FW < 250 nsec) bunches

➢ Note: Muon g-2 uses this system before Mu2e and requires FW < 150 nsec

Each 2.5 MHz bunch is synchronously transferred to the Delivery Ring into a stationary 2.4 MHz bucket

RF Frequency Shift in Recycler to Delivery Ring Transfers

- The circumferences of the Delivery Ring and the Recycler are not harmonically related. $\frac{f_{DR}}{f_{RR}} = \frac{590.0\ \text{kHz}}{89.8\ \text{kHz}} = 6.57 \neq \text{integer}$
- Recycler 2.5 MHz RF operates at h = 28 (f_{RF} = 2.515 MHz)
- Delivery Ring RF system operates at h = 4 (f_{RF} = 2.360 MHz)
- Synchronous transfer is accomplished by a phase jump in the digitally synchronized Low Level RF system that ensures exact phase alignment at Delivery Ring injection time
- A similar system was successfully used during Tevatron Collider Run II for Main Injector to Debuncher beam synchronization during antiproton stacking.

RF Parameters

Parameter	Value	Units
Recycler Ring 2.5 MHz Bunch Formation RF System		
Harmonic Number	28	
Frequency	2.515	MHz
Peak Total Voltage	80	kV
Number of Cavities	7	
Duty Factor	33	%
Bunch Formation time	90	msec
Delivery Ring 2.4 MHz RF System		
Harmonic Number	4	
Frequency	2.360	MHz
Peak Total Voltage	10	kV
Number of Cavities	1	
Duty Factor	27	%
Both Systems		
R/Q	400	Ω
Q	125	
Beam loading Comp. feedback gain	4	

Delivery Ring (DR) Extinction Performance:

- Beam extinction on extraction from the DR is greater than 10^{-4}

Note: the 2.5 MHz Cavities for the Recycler and Delivery Ring are identical

Longitudinal Tracking Models

- Recycler Model
- Delivery Ring Model

Two Stage ESME Model

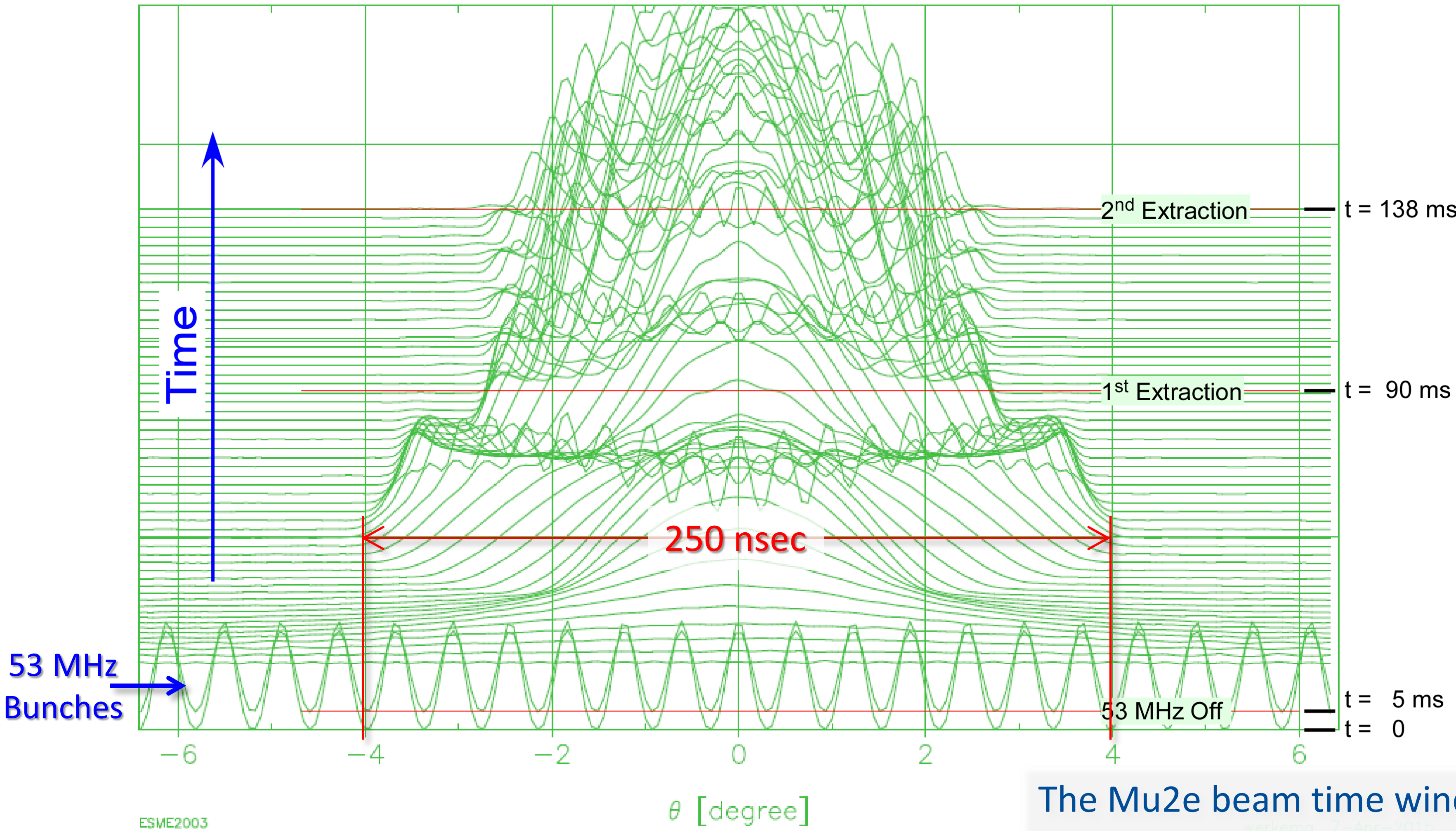
1. Recycler Ring Model

- 10,752,000 protons generated in twenty one (21) 53 MHz buckets. This is done in ten separate runs of 1,752,000 proton each.
- Initial longitudinal emittance of each bunch is 0.10 eV-sec
- Tracked using ESME through Recycler RF manipulations until time of extraction
- Final phase coordinate of each proton is converted to Delivery Ring phase
- Resulting energy and phase of each proton written to disk for use as input to the Delivery Ring Model

2. Delivery Ring Model

- Input = Energy/phase output from Recycler model
- Cavity impedance and space charge effects simulated
- Beam loading compensation simulated by reducing cavity shunt impedance and Q by the beam loading compensation feedback gain (4) and applying an accelerating phase to compensate for energy lost
- Beam is tracked using ESME to various spill times

Recycler RF Model – Time Distribution Waterfall during 2.5 MHz Bunch Formation



Recycler intensity vs. θ from injection to the time of extraction of the 2nd bunch.
Trace separation: 207 turns = 2.30 msec.
$\theta = 2\pi f_{rev}\Delta t$, $1° = 31$ nsec

The Mu2e beam time window is defined to be the center of the RF bucket ±125 nsec

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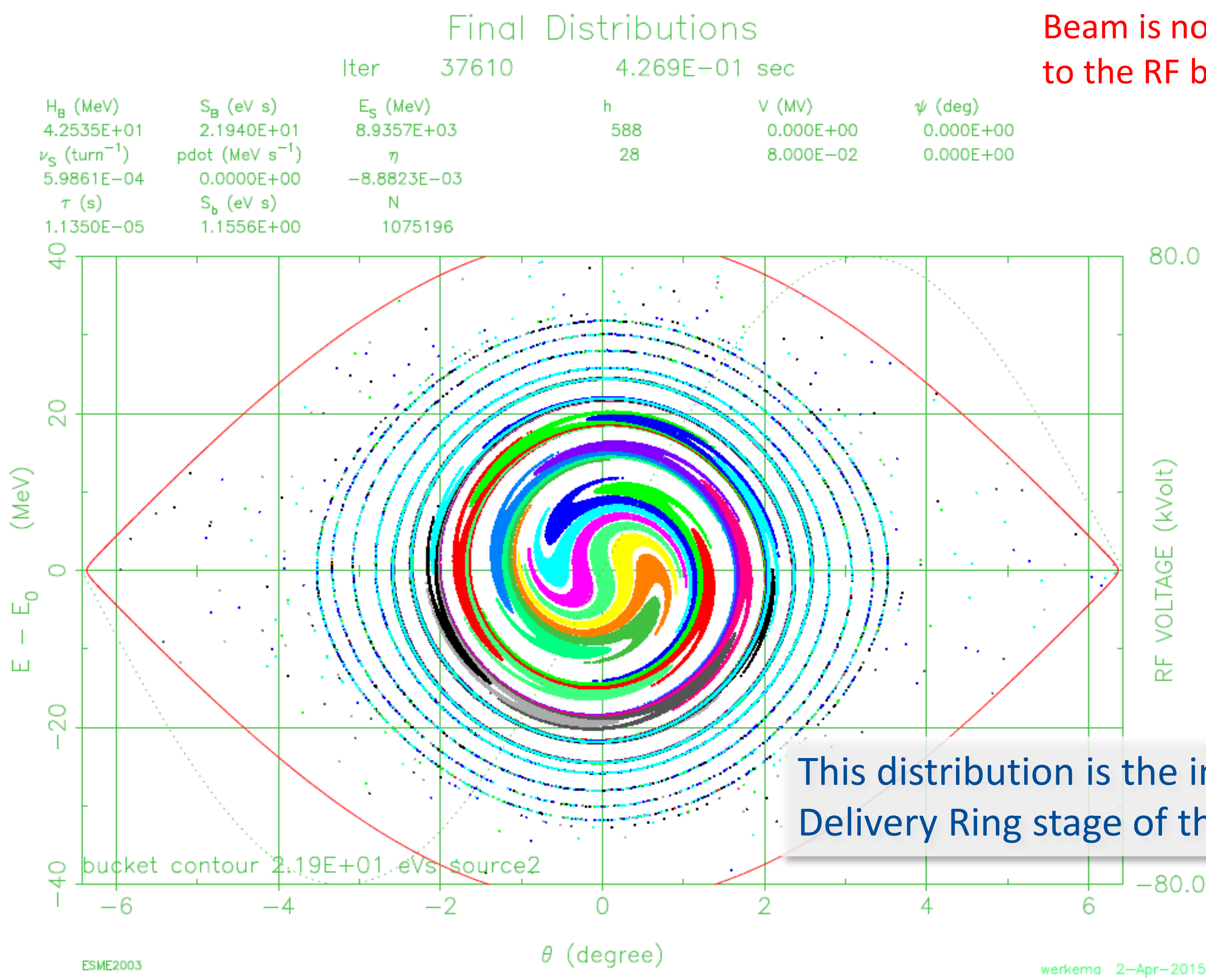
Recycler Longitudinal Phase Space at Extraction Time for Bunch 2

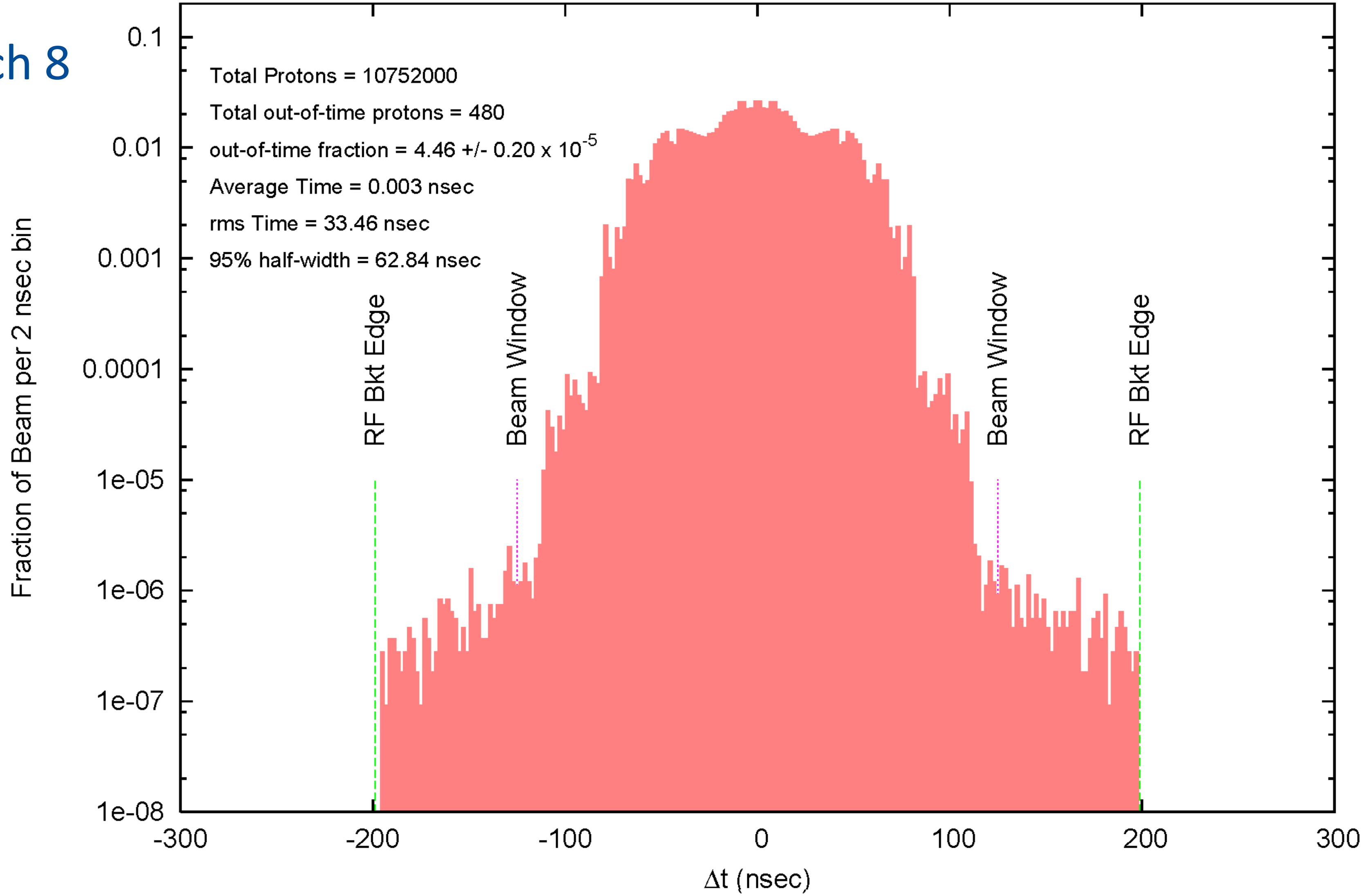


Beam is not matched to the RF bucket.

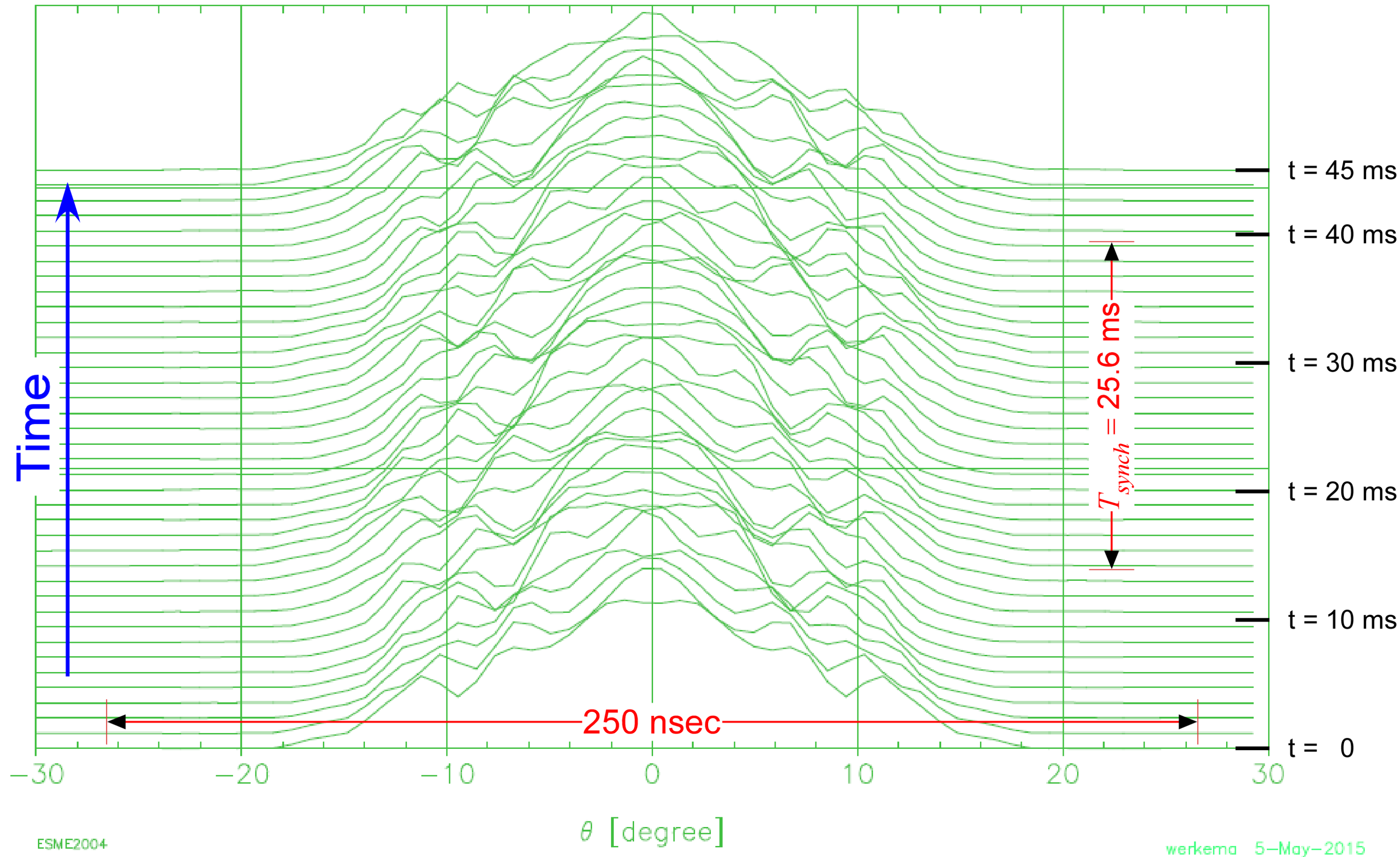
This distribution is the input to the Delivery Ring stage of the model

Recycler Proton Time Distributions at Extraction Time

Bunch 8

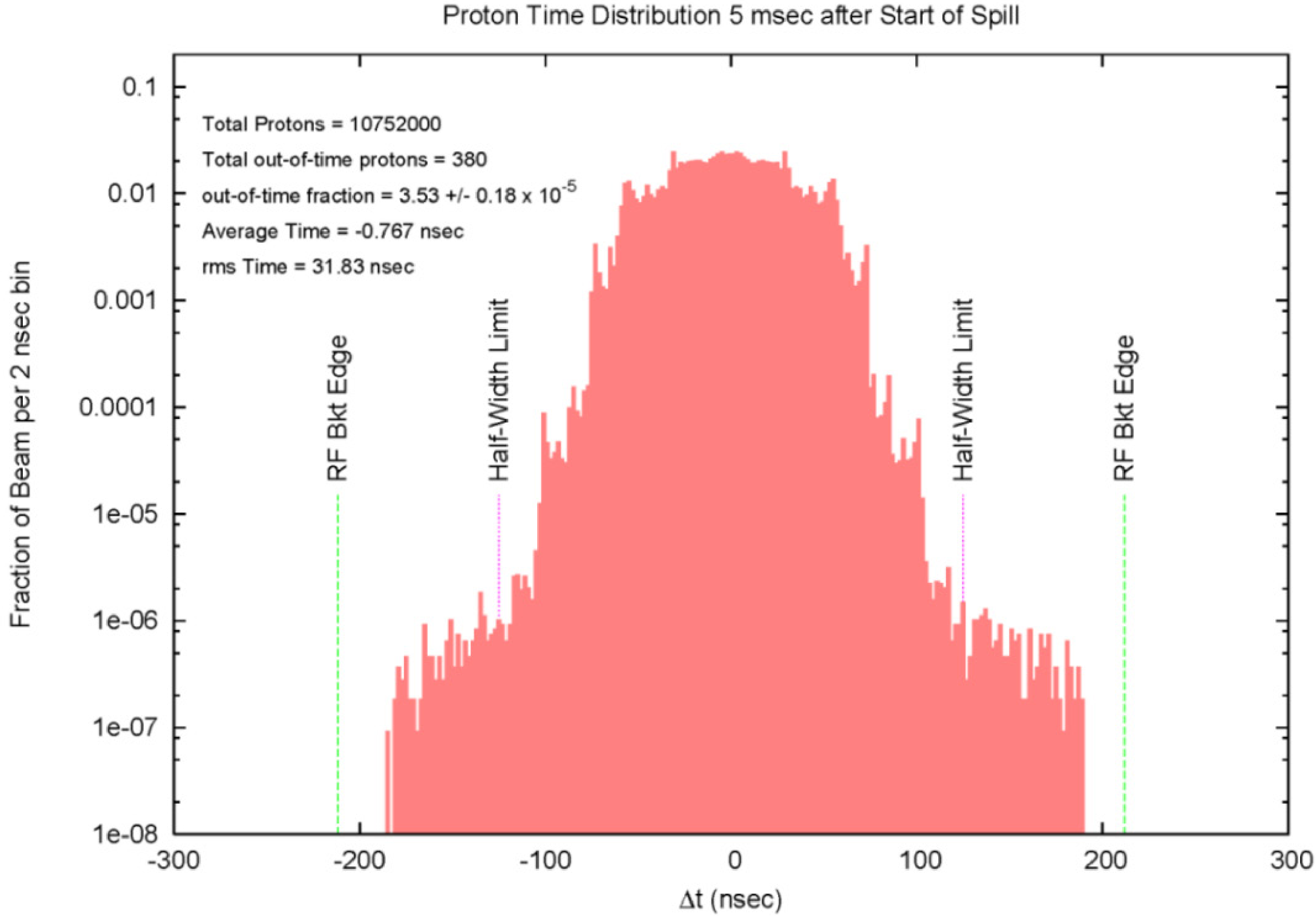


Delivery Ring Model

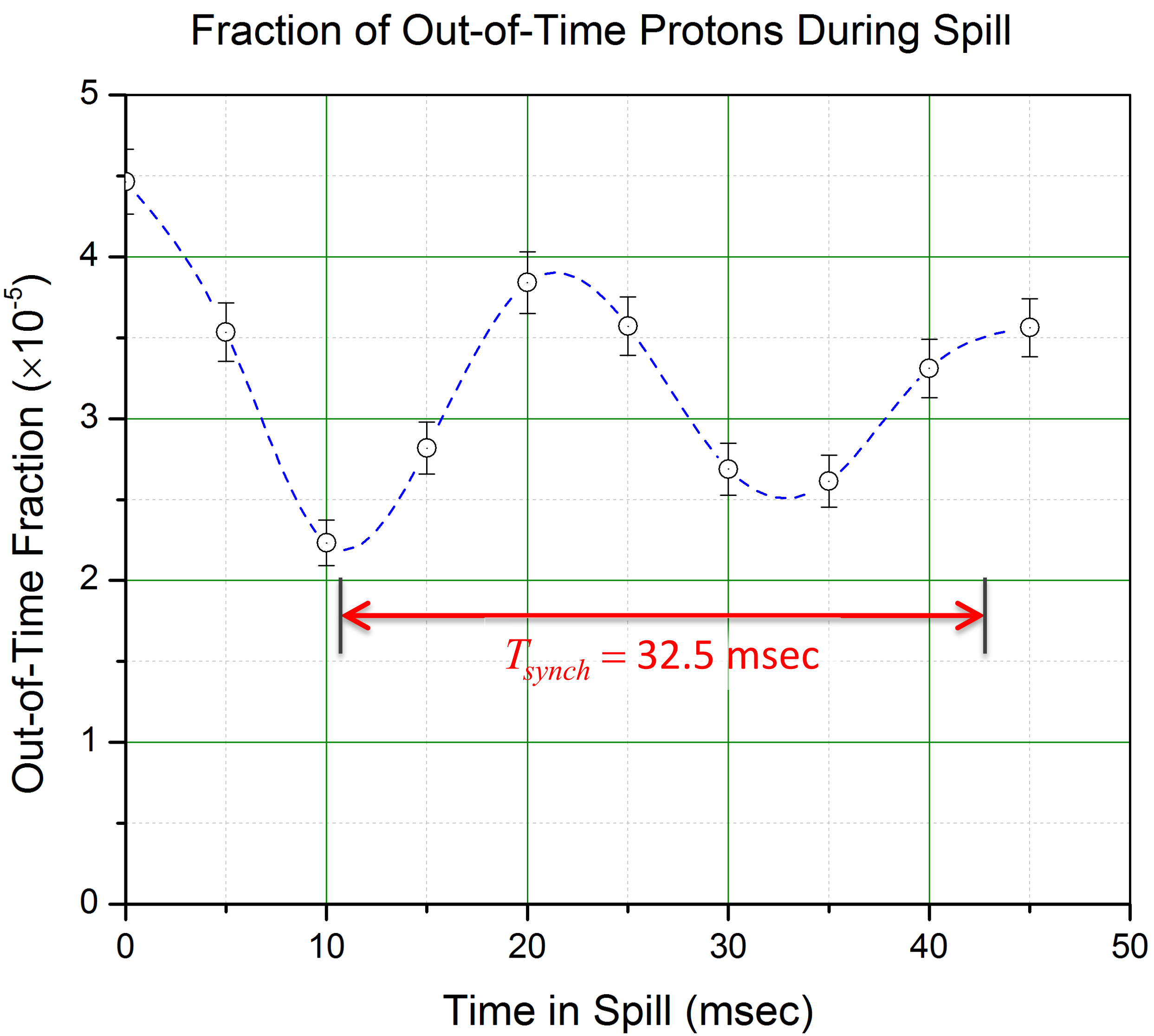


Delivery Ring longitudinal distribution vs. θ for 45 msec of spill time.
Trace separation: 664 turns = 1.125 msec.
$\theta = 2\pi f_{rev}\Delta t$, 1° = 4.71 nsec

Delivery Ring Proton Time Distribution During Spill Animation



Variation of the Out-of-Time Fraction Over a 45 msec Spill



Not particularly well correlated with synchrotron period.

Note: the T_{synch} shown here is that of a proton 125 nsec from the center of the RF bucket. This is larger than the small amplitude synchrotron period.

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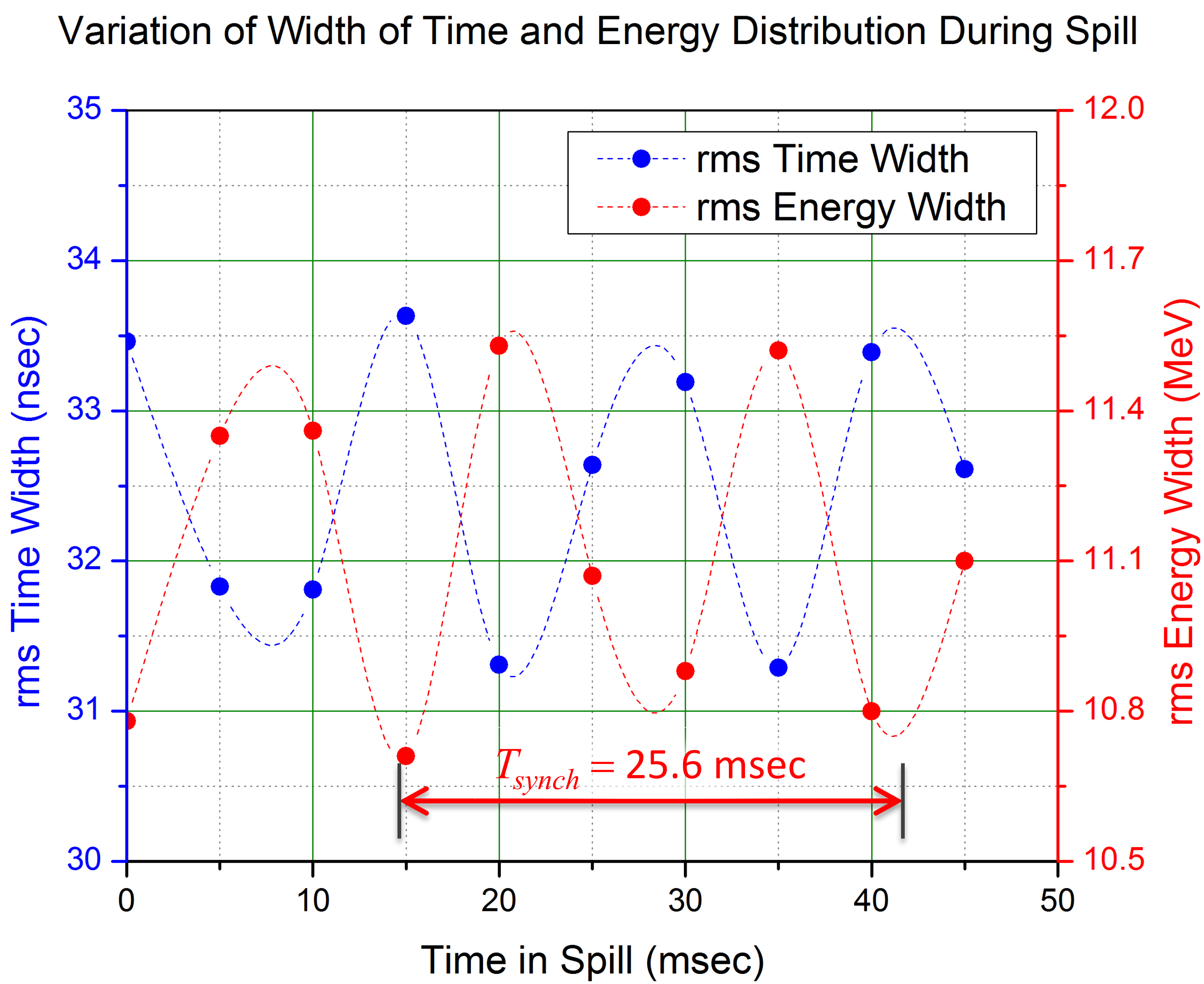
Variation of RMS Energy and Time Width



RMS widths oscillate at twice the synchrotron frequency as expected.

Note: the T_{synch} given here is the small amplitude synchrotron frequency.

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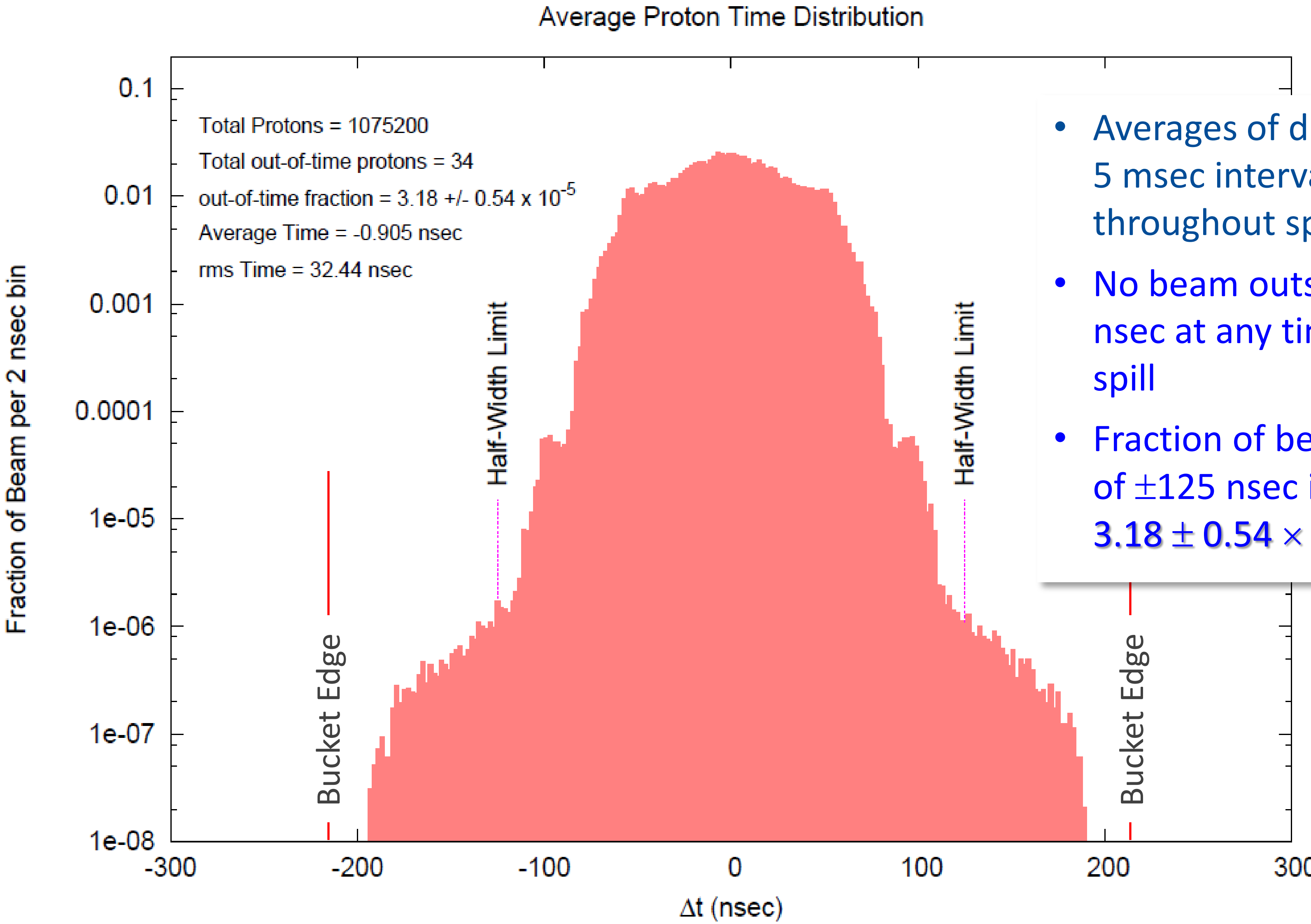
The Average Beam Pulse – Time



- Averages of distributions at 5 msec intervals throughout spill
- No beam outside of ±200 nsec at any time during spill
- Fraction of beam outside of ±125 nsec is: **$3.18 \pm 0.54 \times 10^{-5}$**

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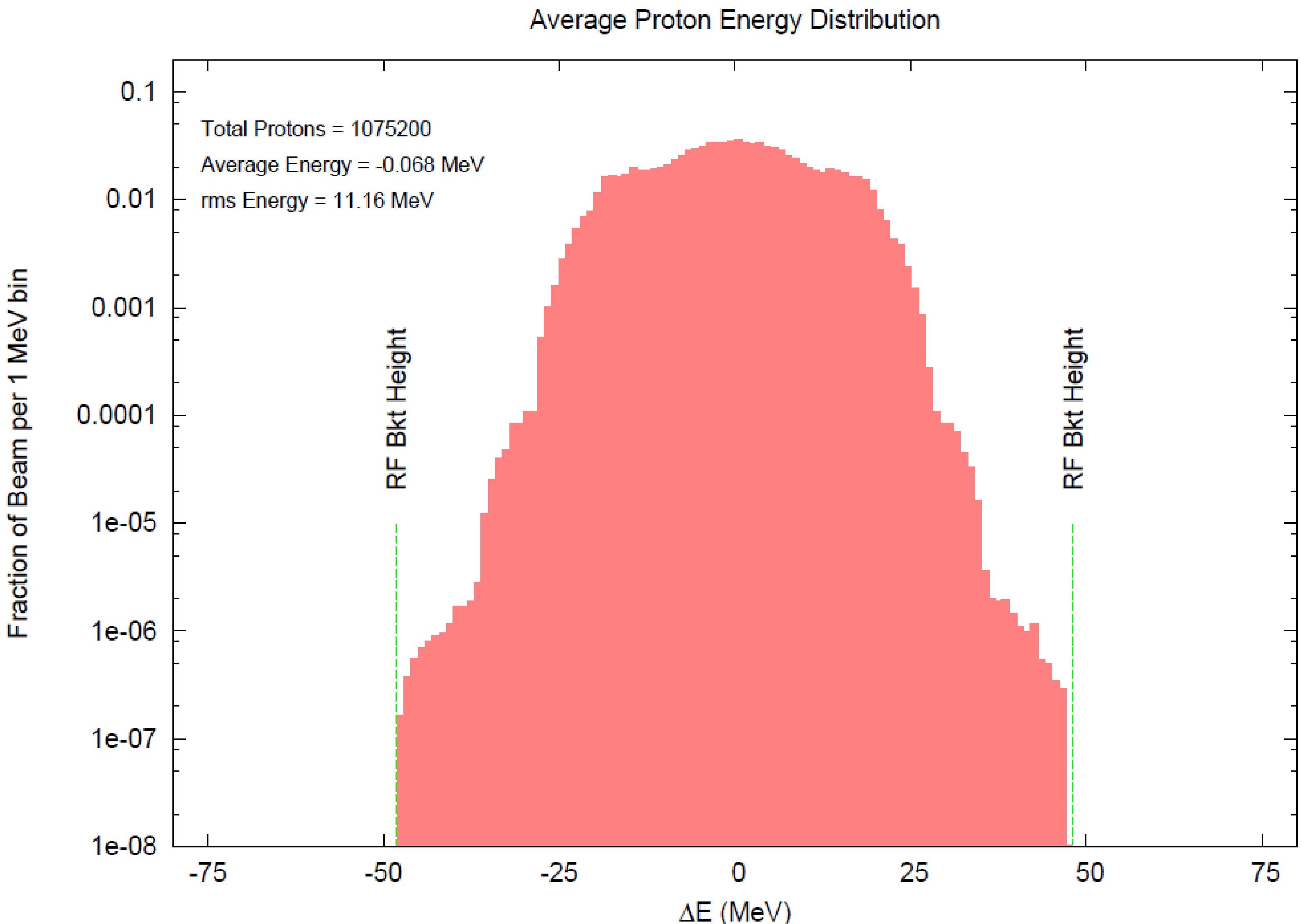
The Average Beam Pulse – Energy



Conclusions

- Longitudinal tracking models have been constructed that simulate the development of the longitudinal phase space of the Mu2e primary proton beam up to the time of extraction from the Delivery Ring
- These models predict a beam extinction level of $3.18 \pm 0.54 \times 10^{-5}$ for beam upstream of the M4 extinction insert

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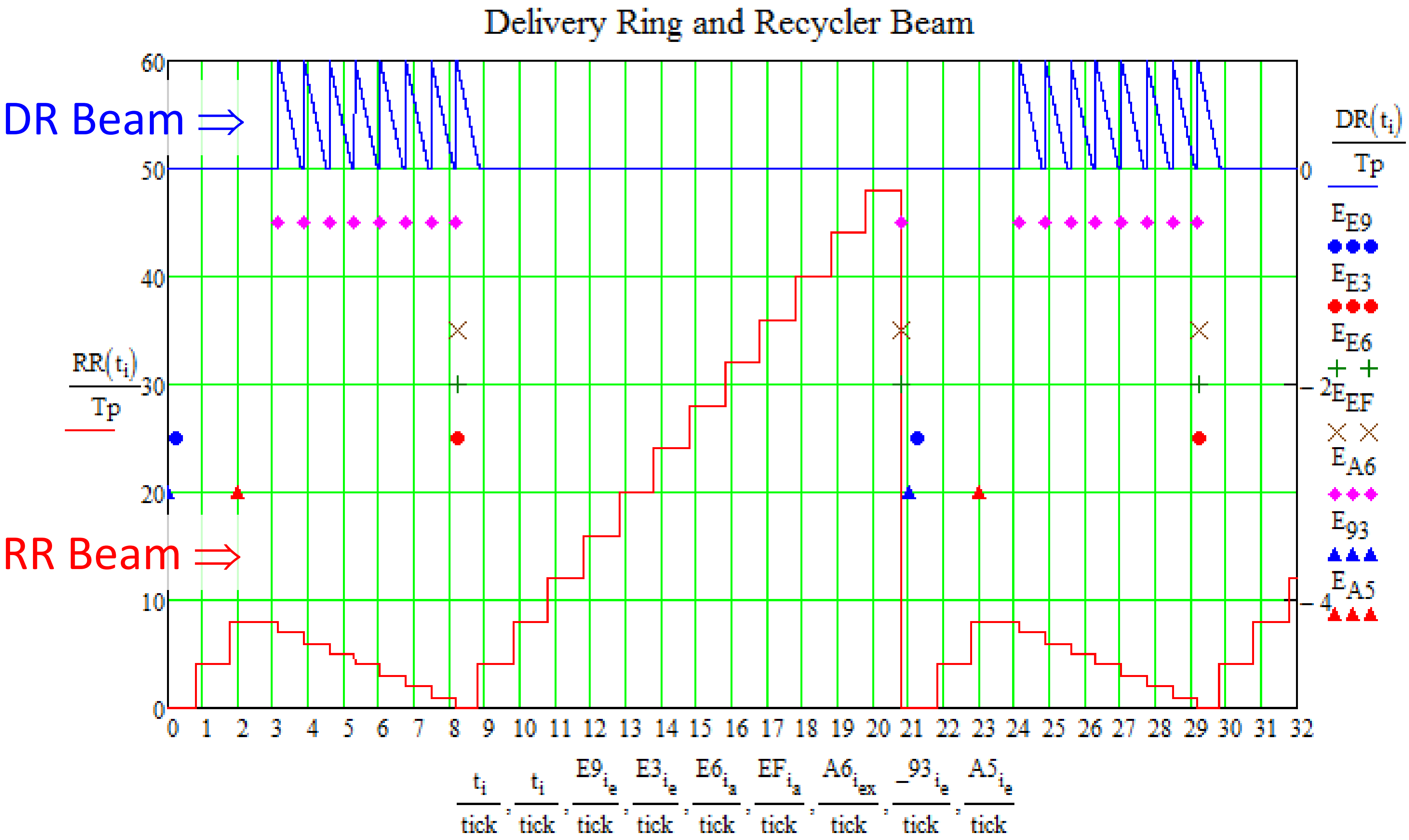
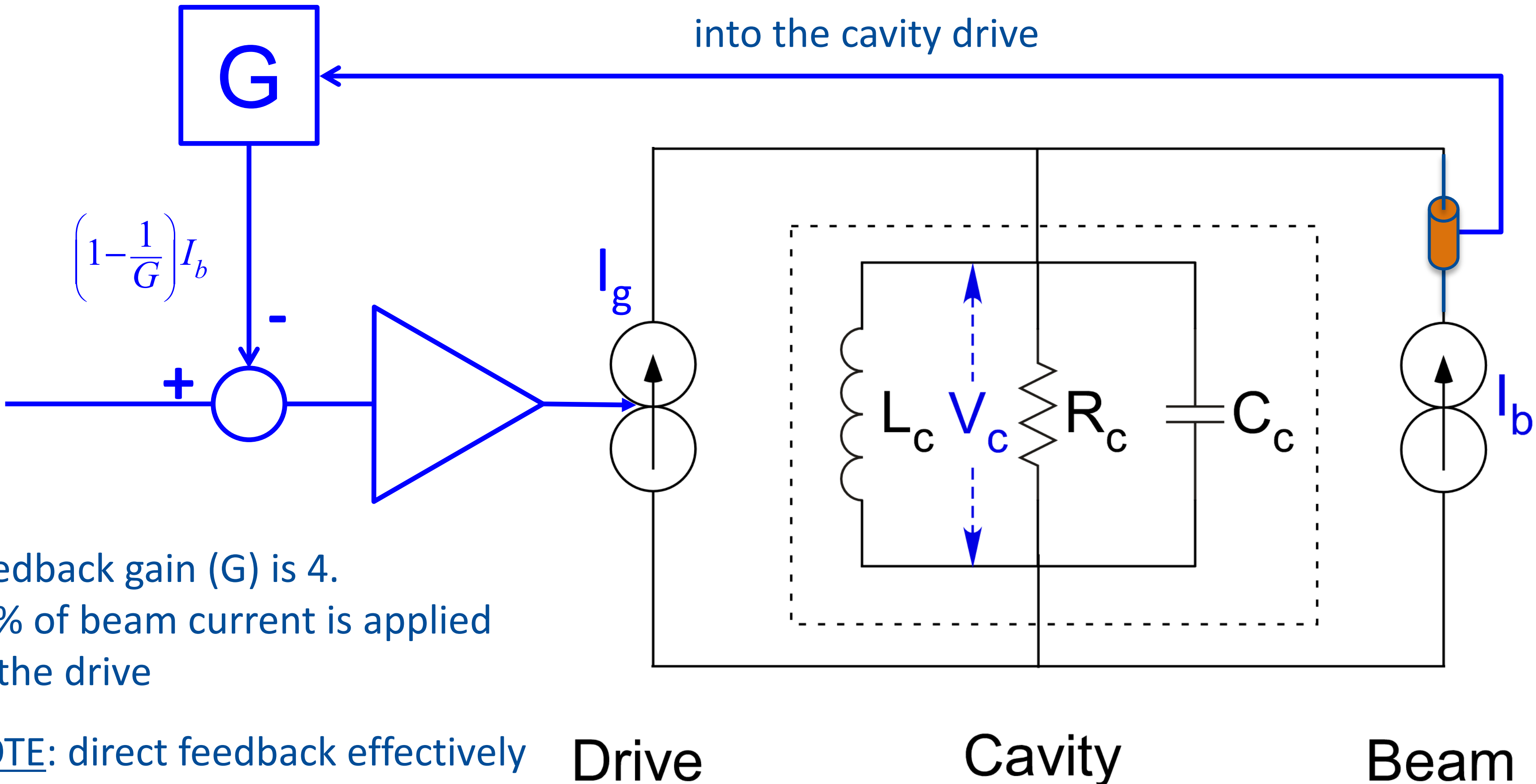
Backup Slides

Mu2e / NOvA Accelerator Timeline Model



2.5 MHz RF Beam Loading Compensation

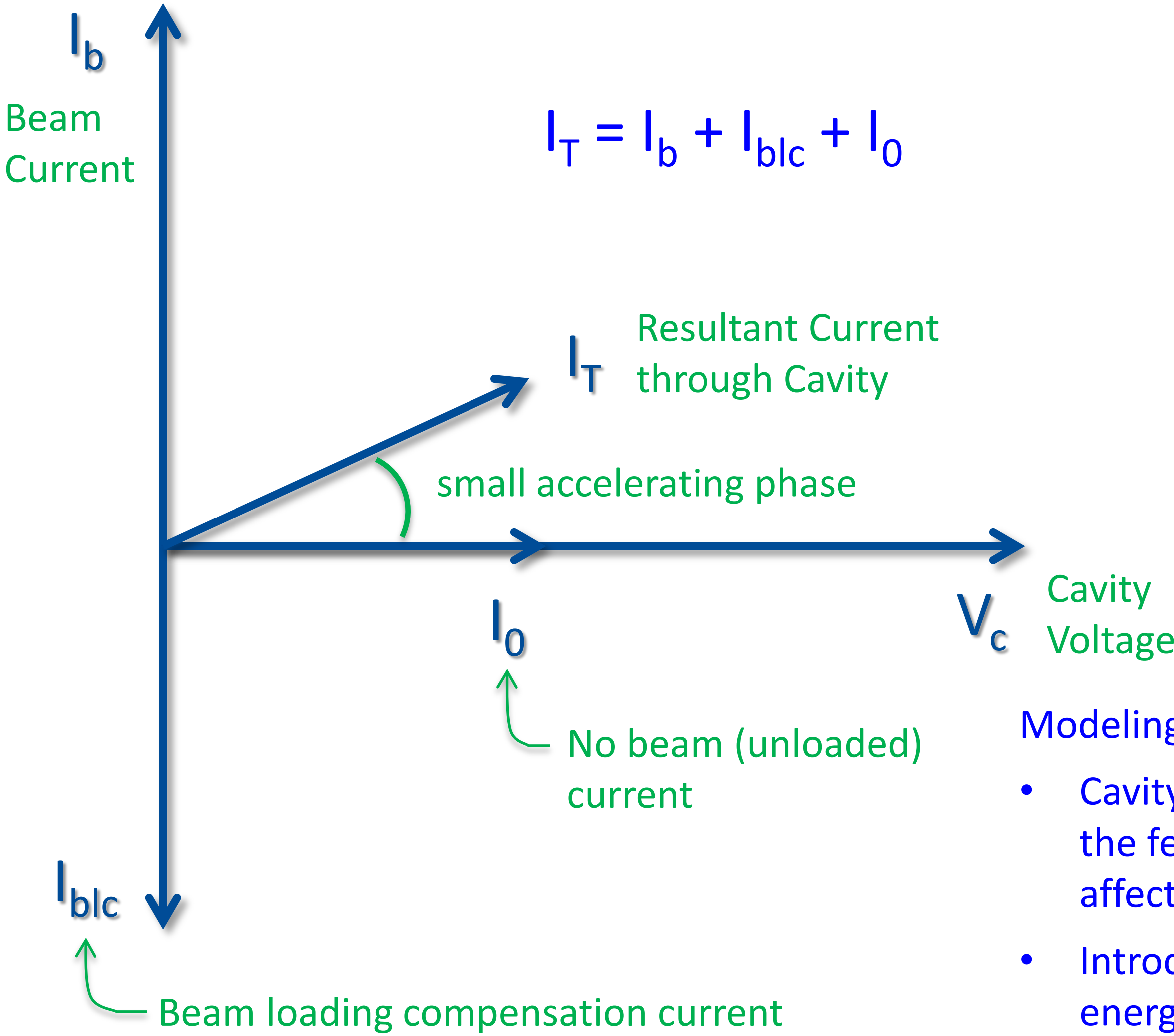
Detect and feed back the beam current into the cavity drive



Feedback gain (G) is 4.
75% of beam current is applied to the drive

<u>NOTE</u>: direct feedback effectively reduces the impedance and Q of the cavity by a factor of G.

Application of Beam Loading Compensation to Delivery Ring Model



Result is:

- The required voltage (10 kV) is applied to the cavity
- There is a small accelerating phase (which is compensated in the actual RF system by phase feedback)

Modeling this is done by the following:

- Cavity impedance and Q is reduced by the feedback gain (4×) (Note: R/Q is not affected)
- Introduce a phase ramp to keep the energy constant

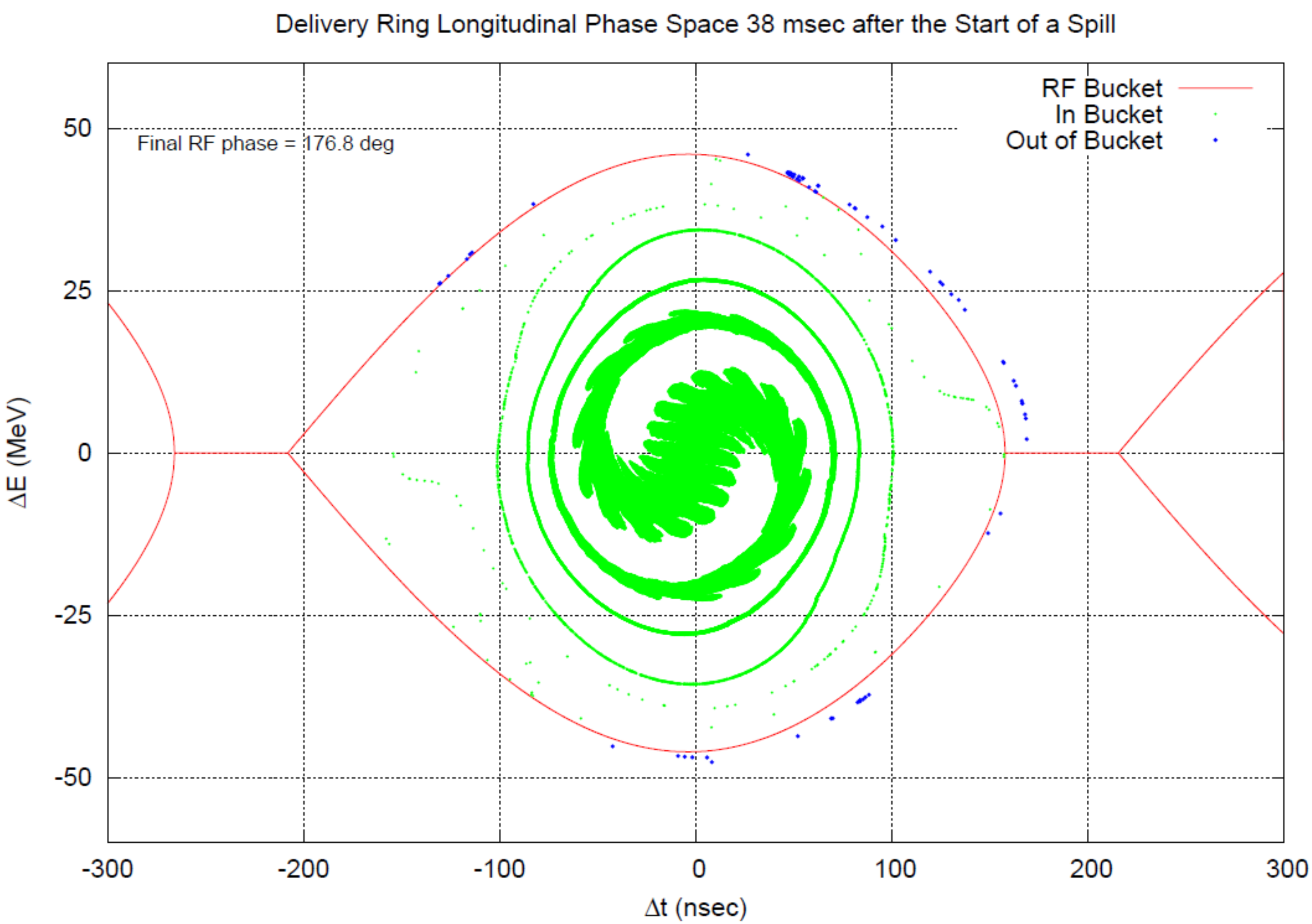
Delivery Ring Beam Loading Compensation Model Results

Smaller RF bucket due to phase ramp

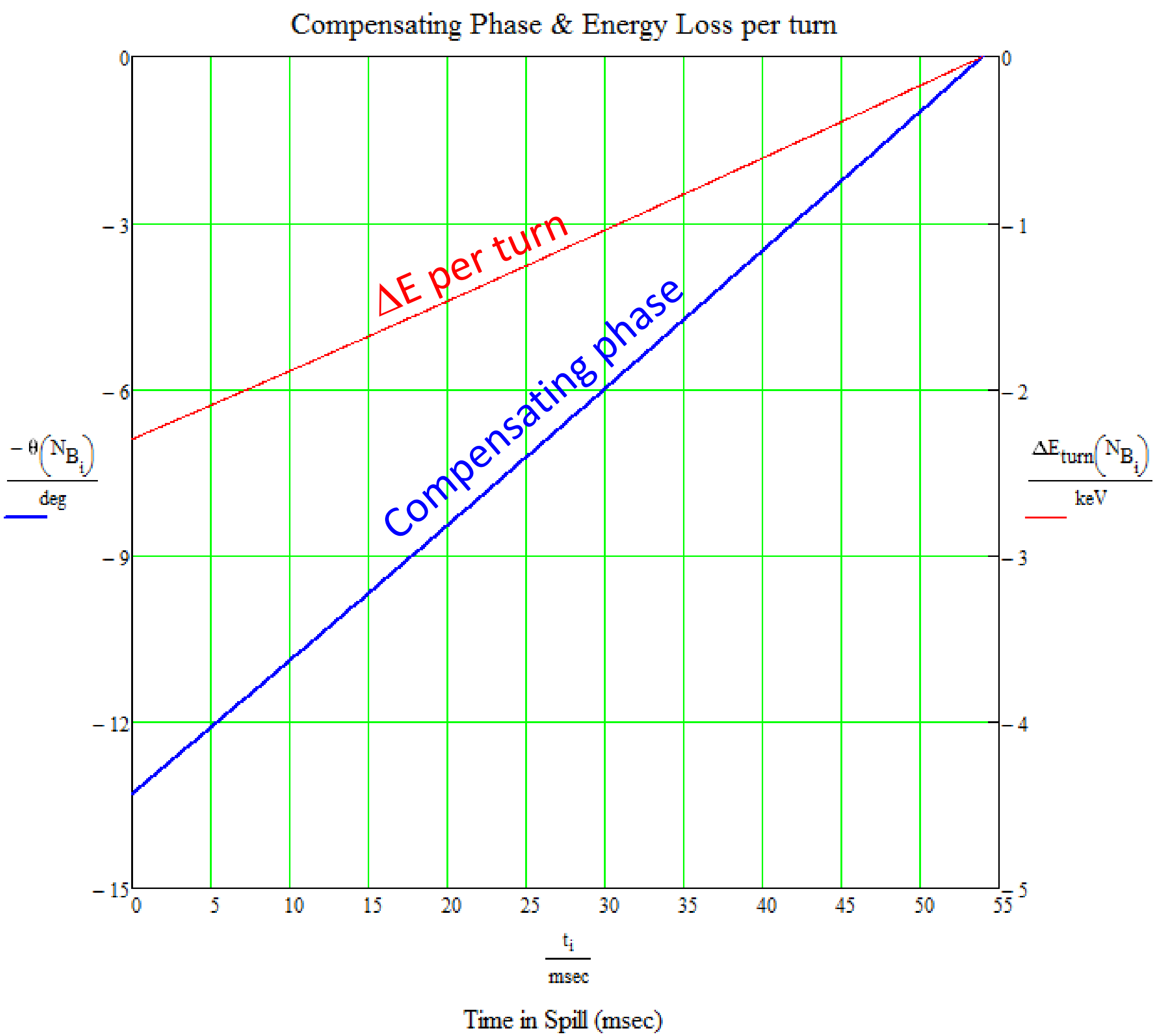
- this will not be present in the real system
- makes model conservative

Fewer protons outside the bucket.

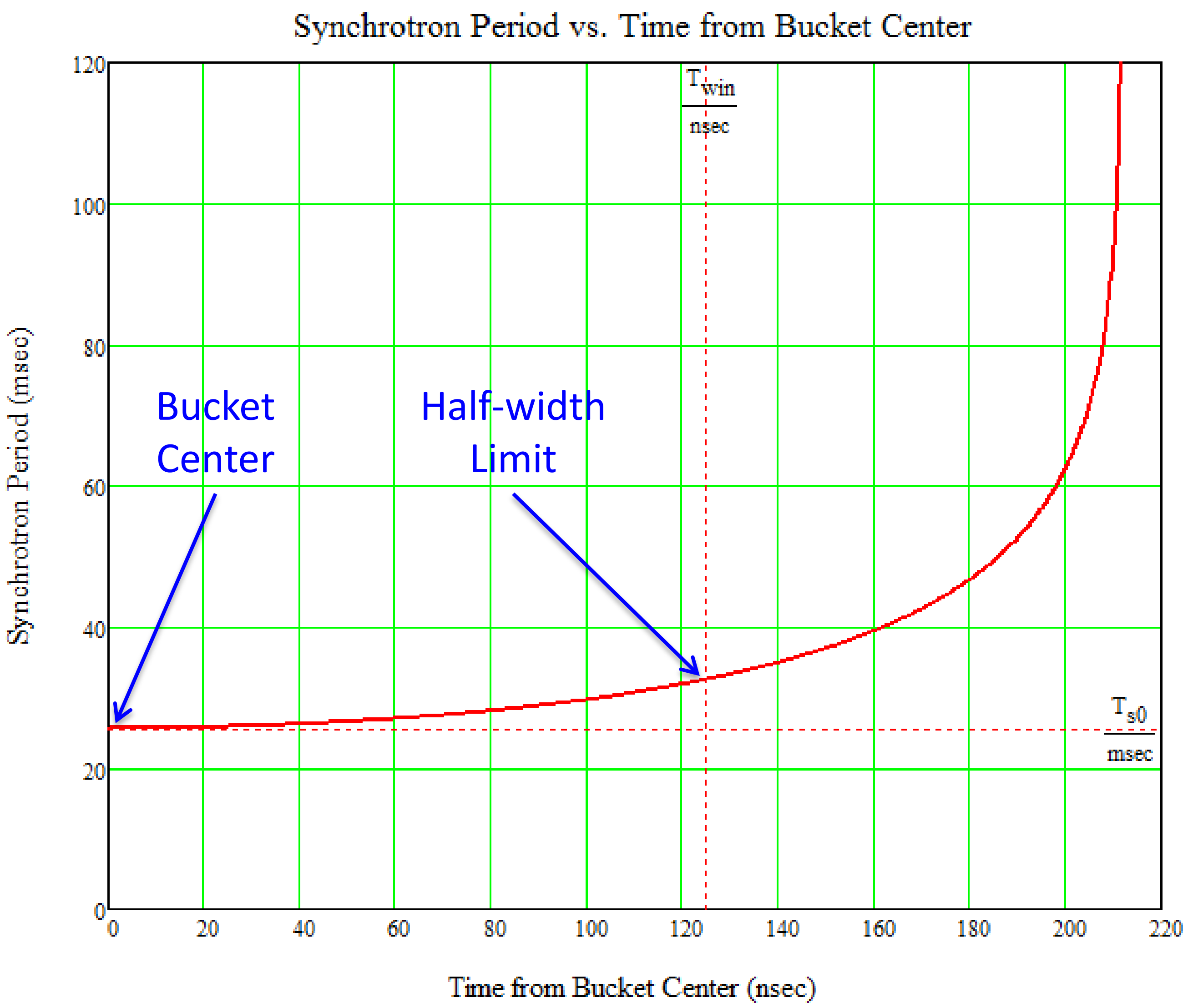
Beam does not stray far from bucket – no beam outside of $\pm$200 nsec.



Beam Loading Compensation Model Phase Ramp



Delivery Ring Synchrotron Period as a Function of Δt



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